X-ray Observations of the Intergalactic Medium

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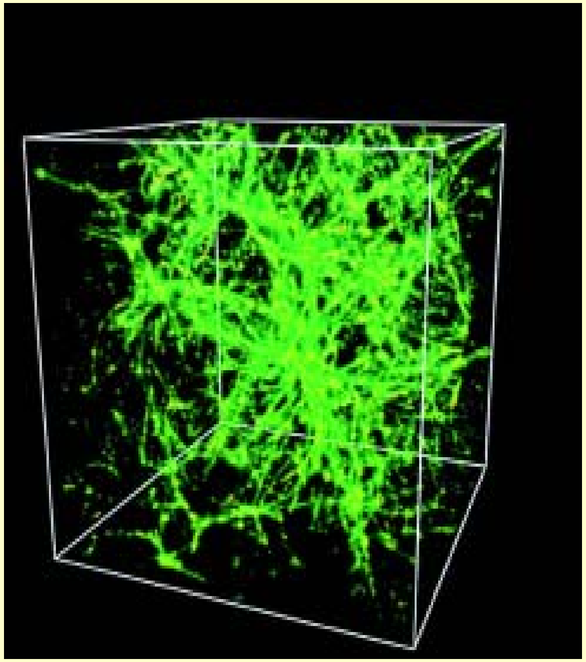
1. 'How Dark Is the X-ray Sky?'

- One of the primary goals of Chandra: determine nature of the XRB;
- 80% of the Soft XRB resolved into point sources
  How much diffuse emission left, and what is it?

Direct Baryon Inventory:

- Big Bang Nucleosynthesis, Abundances of light elements: ρ(baryons)
- $\Omega_B = 0.04$ expected;
- $\Omega_B = 0.04$ at $z = 3$ (Ly α forest)
- $\Omega_B = 0.02$ at $z = 0$ in stars and gas! (Fukugita, Hogan, Peebles 1998)

Half the baryons 'missing' at $z = 0$?



Cen and Ostriker, 1999; and others since

Coupled Dark Matter/Hydrodynamic Simulations:

Half the ordinary matter could be in a tenuous, highly ionized Intergalactic Medium- the 'Warm/Hot IGM' (WHIM)

Material 'left over' from structure formation; lowest density phase, not yet undergone gravitational collapse; heated by shock waves induced by gravitational collapse.

Expected Properties of the WHIM:

- Density contrast: $\delta \sim 10\text{-}30$
- Density: $< n_b > = 2 \times 10^{-7}$ cm^{-3}
- Broad distribution: $\Delta \log n \sim 1$
- Clumping: $C = < n_b{}^2 > / < n_b >^2 \sim 100$
- Temperature $T \sim 4 \times 10^6$ K, but ranges between 10^5 and 10^7 K at each n
- Metallicity: ? Ly α forest, $z = 3$: $Z/Z_O \sim 0.01$
- Groups, clusters, $z \sim 0$: $Z/Z_O \sim 0.1\text{-}0.3$
- Probably strongly density-dependent
- Densities very low: equilibration timescales very long !

Detection/characterization:

High ionization: principal radiative interactions in X-ray band;
Focus on H-, He-like O, Ne ($Z < 8$ very highly ionized)

Absorption Studies

- Requires high resolution: diffraction grating spectrometers
- Focus on n = 1-2, O VII, O VIII (577, 653 eV/ 21.6,19.0 A)
- Expected EW: $\Delta v_{\mathrm{thermal}} = (kT/m)^{\mathbf{1/2}} = 23\ T_6^{\mathbf{1/2}}$ km/sec:
- Saturation at column density $N = 2.10^{\mathbf{15}}\ (\Delta v/23\ \mathrm{km/s})\ \mathrm{cm}^{\mathbf{-2}}$
    - Compare: $N \sim 3.10^{\mathbf{14}}\ \delta\ (l/10\ \mathrm{Mpc})\ [(Z/Z_{\mathrm{O}})/0.1]\ \mathrm{cm}^{\mathbf{-2}}$
    - **Saturation at δ ~ 10 !**

So we're looking at EW ~ 100 km/sec
0.2 eV
7 mA

and that requires resolving power $\lambda/\Delta\lambda \sim 3000$!

Absorption Studies (continued)

Detectability will depend strongly on Δv and on $Z/Z_{\odot}$

Δv: set by expansion of the Universe and gravitational amplification; detection of absorption lines may initially tell us more about velocity fields and abundances than about the baryon density!

Simulations predict:

one system EW > 100 km/sec in random direction, out to $z \sim 0.3$

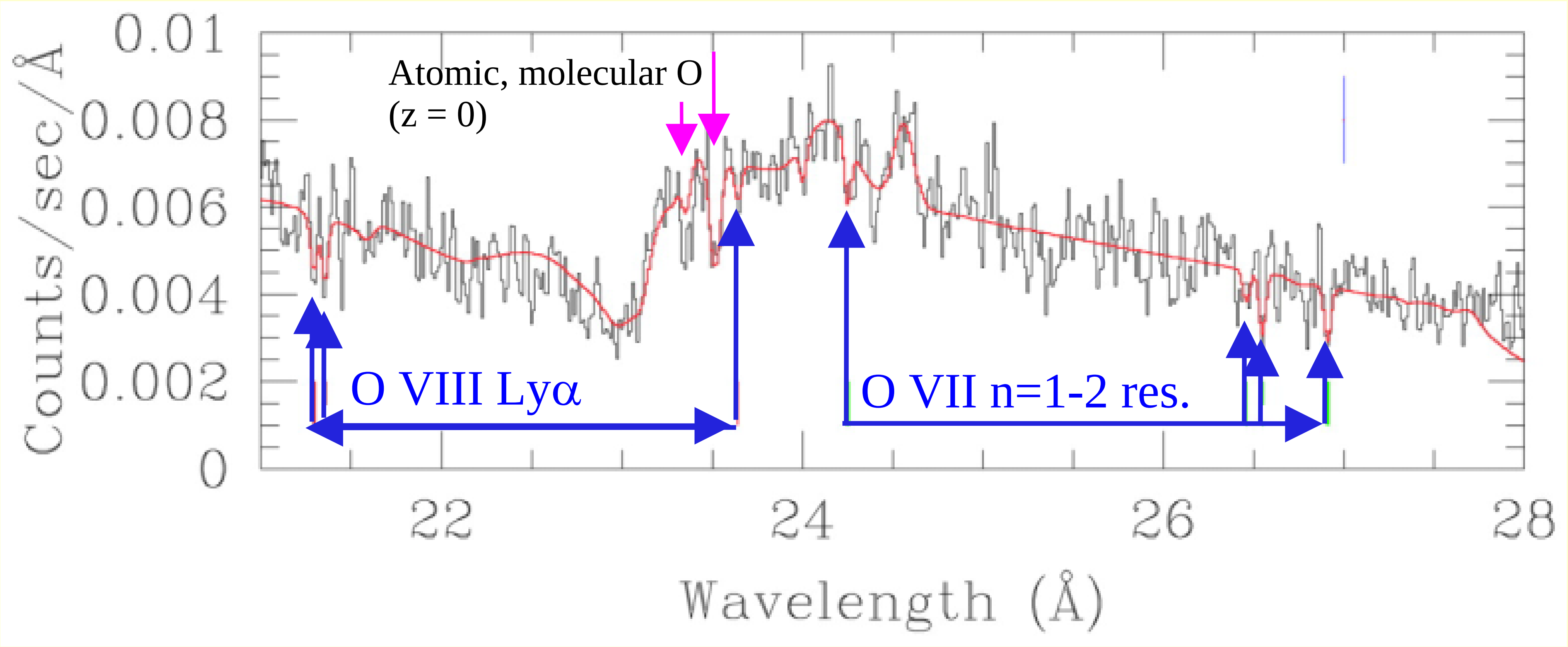
four systems EW > 30 km/sec in random direction, out to $z \sim 0.3$ (Hellsten et al. 1998)

Absorption Spectroscopy (*z* > 0): Observational Evidence

PKS2149-306	Chandra	HETGS	Fang et al. 2001
S5 0836+710	“	“	“
H1821+643	“	“	Fang et al. 2001a
H1821+643	“	LETGS	Mathur et al. 2003
PKS2155-304	“	LETGS	Fang et al. 2002b
Mkn 421	XMM	RGS	Cagnoni 2002
Mkn 421	Chandra	LETGS	Nicastro et al. 2003

(z > 0 absorption detection claimed)

Absorption Spectroscopy: H1821+643 (z=0.297), Chandra LETGS



Mathur, Weinberg, Chen, *Ap.J.*, **582**, 82 (2003)

- Weak line absorption at four out of six known O VI absorbers
- Two coincidences O VII/VIII (z = 0.12, 0.25)
- All weak features (2σ); larger fluctuations present in data

Probably safest regarded as upper limits

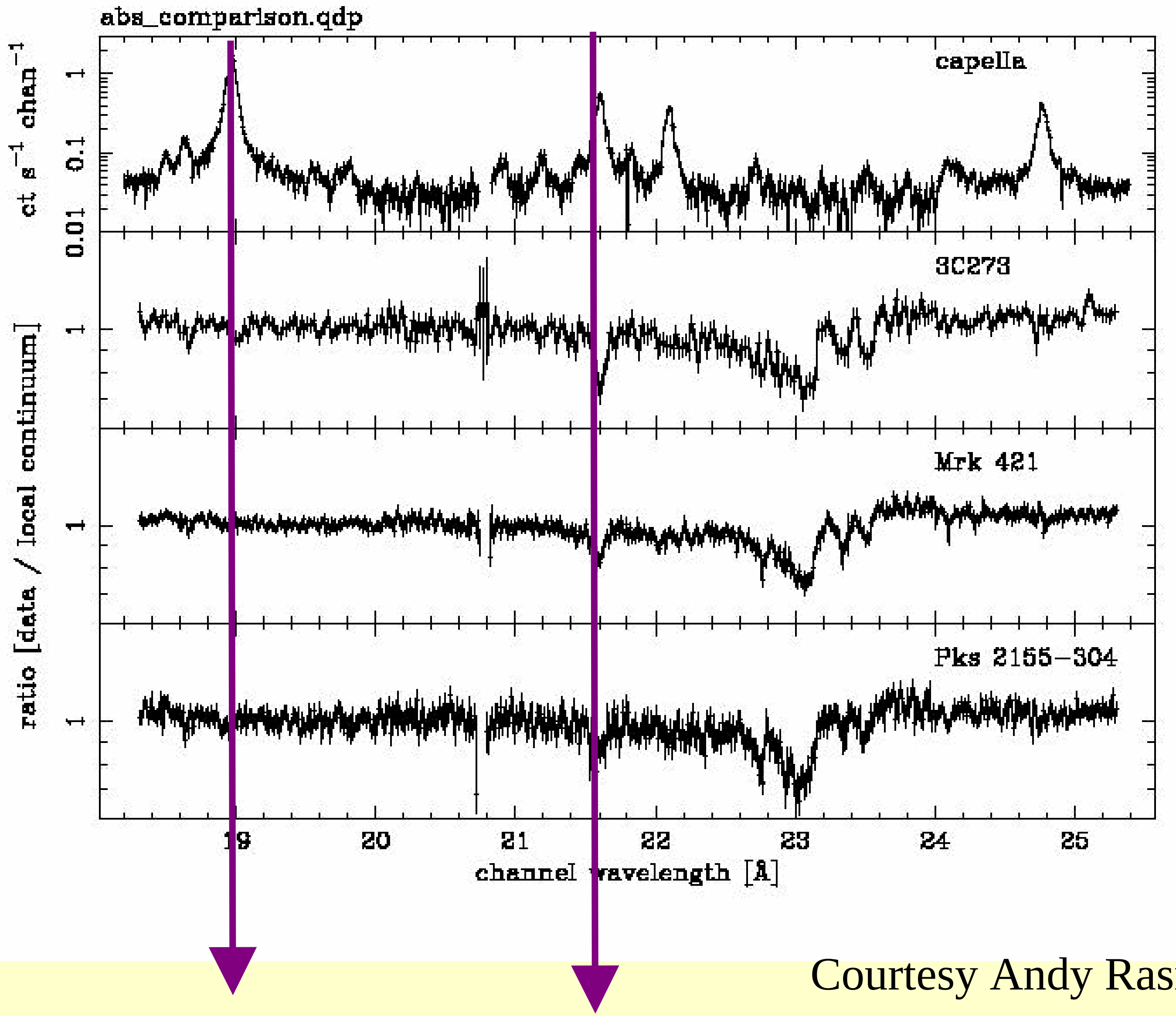
Absorption Spectroscopy (continued)

* PKS2155-304: O VIII Lyα z = 0.055: not present in other data
* Mkn 421: O VII n=1-2 resonance absorption reported:
  z = 0.01 RGS/LETGS, z = 0.025: LETGS; EW ~ 3-4 mA

* Possible detection in Mkn 421.

* We should be close at current sensitivity: predict 5-10 systems N(O VII) > 10^{15} cm^{-2} per unit redshift; surveyed about 0.3
* Will be difficult to increase statistics: lack of bright sources, exposure times already of order 1 Msec.
* Promising avenue: monitor nearby BL Lac's and take advantage of occasional outbursts (Mkn 421, Nicastro et al. 2003)
* Won't see a 'Forest' until Constellation-X/XEUS

Absorption Spectroscopy (continued): z = 0



Courtesy Andy Rasmussen

O VIII Lyα

O VII n = 1-2 resonance

XMM/RGS; several 100 ksec exposure per source

Absorption Spectroscopy (continued): $z = 0$

* Absorption also present in Chandra spectroscopy: first announced (PKS2155-304) by Nicastro et al. (2002), and several other sources.

* Interpretation:

assume collisional equilibrium; ionization balance
implies $T_e \sim 3.10^6$ K: expected virial temperature of the Local Group;

Column densities + limits on emission line intensities (XQC experiment, McCammon et al. 2003); assume 0.1 Solar O abundance

$n_e < 2.10^4$ cm^{-3} ; $l > 200$ kpc: Local Group ICM!

NB: difficulties with photoionization equilibrium interpretation
(density very low, size ~ 10 Mpc, but lines unresolved in RGS)

Emission Studies: Broad Band

So far: all ROSAT (short focal length, large FOV!)

- Qingde Wang: isotropic excess intensity near ¾ keV
- Scharf et al. 2000: blank field
- Kull & Bohringer 1999; Tittley & Henriksen 2001: cluster environments
- Zappacosta et al. 2002, Warwick et al. 1998: Lockman Hole
- Kaastra et al. 2003: redshifted O VII near clusters

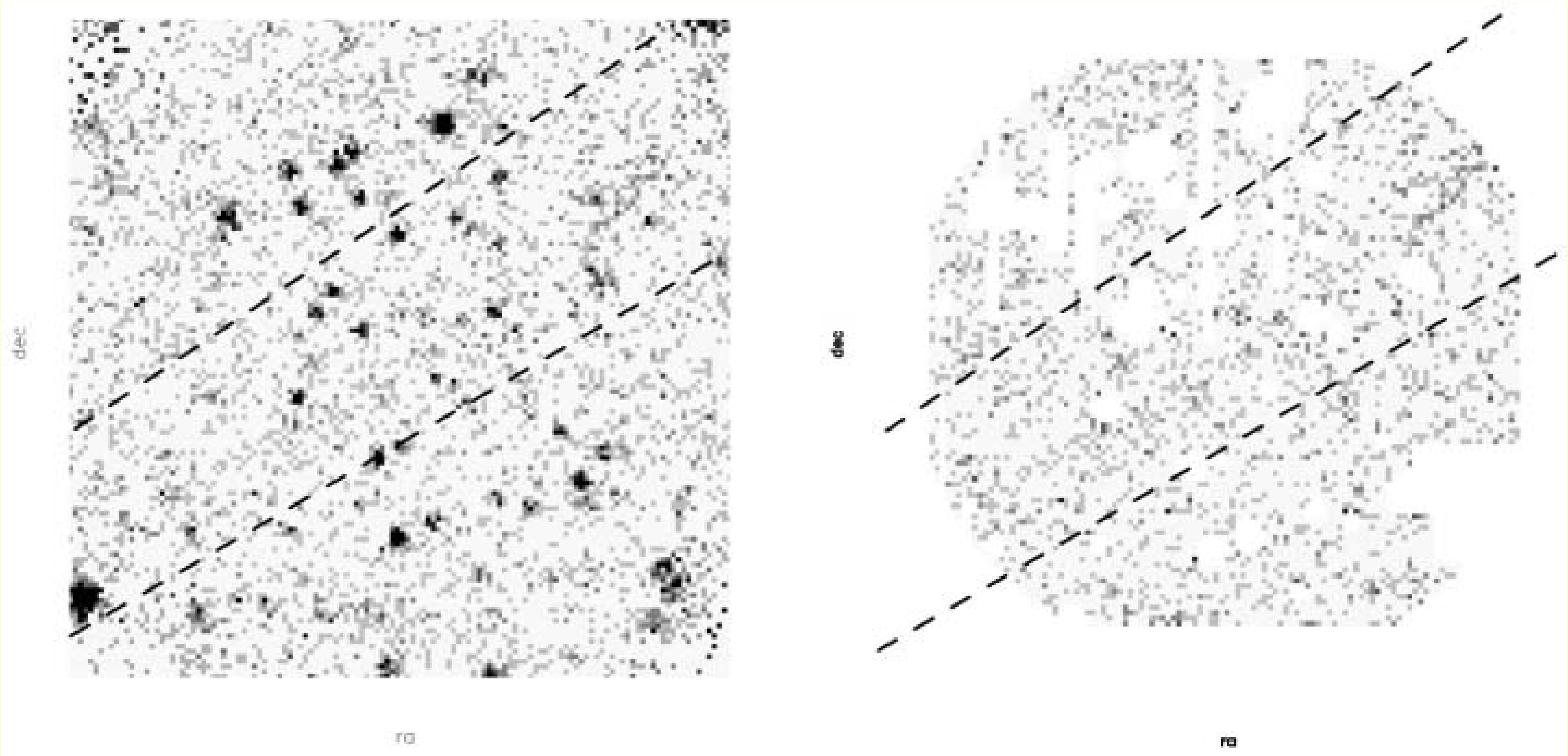
Scharf Filament: $I \sim 6.10^{-13}$ erg cm^{-2} s^{-1} deg^{-2} (0.5-2 keV; S/N ~3)

$\delta \sim 50$?

Zappacosta et al.: $I \sim 10^{-12}$ erg cm^{-2} s^{-1} deg^{-2}; $\delta \sim 100$?

Both correlate with Galaxy overdensity; Scharf Filament may be the WHIM, away from virialized regions; $z \sim 0.3$-0.5

Emission Studies: Broad Band



Scharf Filament: ROSAT 0.5-2 keV

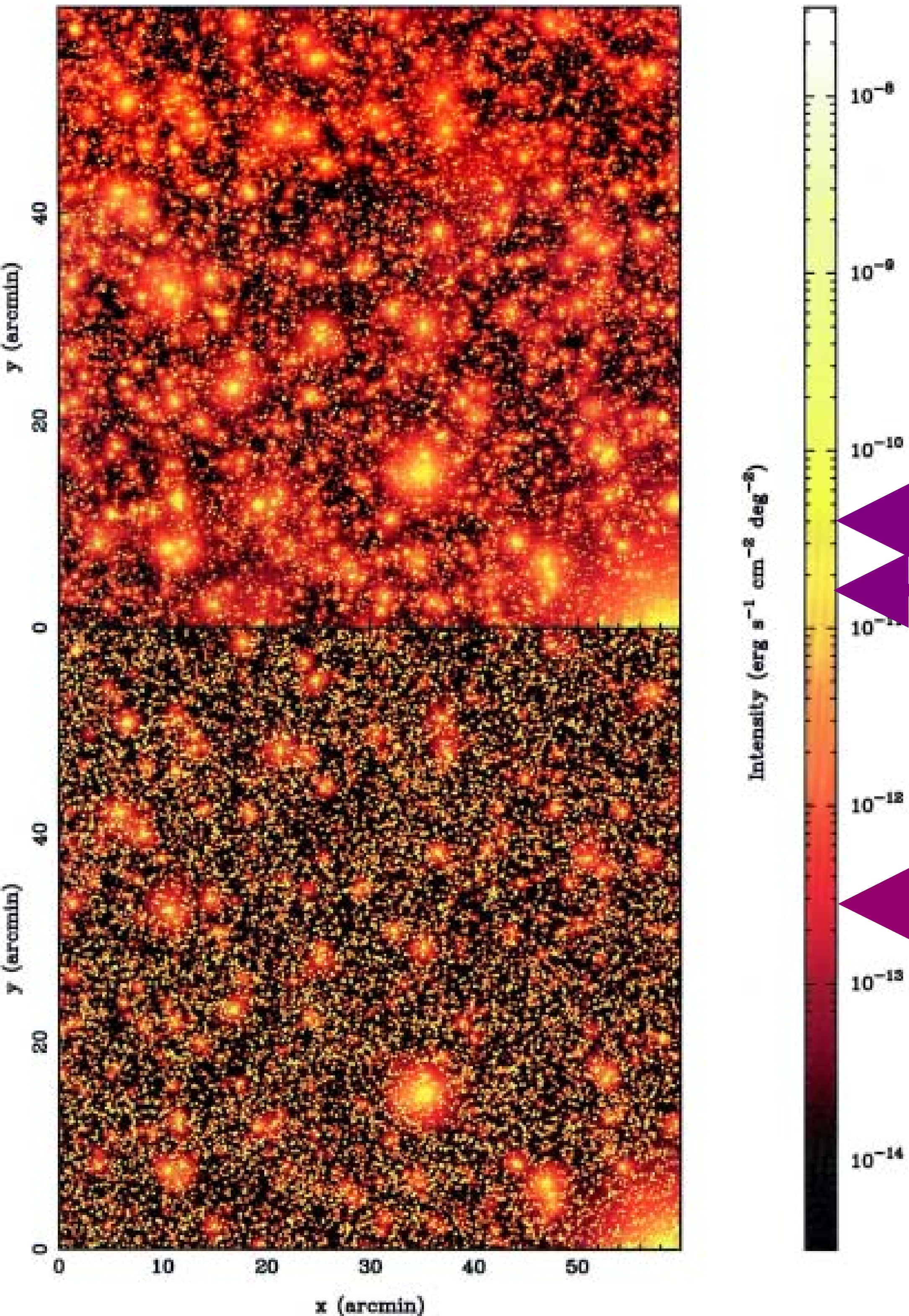
Emission Studies: Broad Band

T ~ 10^{6} K: $I \sim n_e^{2}\, l\, \Lambda(T)/4\pi$ in bremsstrahlung

$$\sim 3.10^{-13}\,(\delta/30)^{2}\,(l/10\ \mathrm{Mpc})\,(\Lambda/10^{-23})\ \mathrm{erg\ cm^{-2}\ s^{-2}\ deg^{-2}}$$

Agrees with results from DM/Hydro Large Scale simulations
Emission heavily weighted towards high overdensities ($I \sim \delta^{2}$):

Need to get to $\delta \sim 10 - 30$ in order to catch at least half the mass density in the WHIM!



Emission Studies: Broad Band

Simulated background: 1 deg^2
Croft et al. 2001

Includes the point sources

Typical CCD particle background,
F ~ 10 m

Groups, Clusters

Intensity corresponds to
average WHIM density !

Broad-band soft image dominated
by virialized objects;
contrast problem!
TOUGH TO IMPOSSIBLE

Spectroscopic Imaging of the Intergalactic Medium

Enhance contrast by imaging in narrow emission lines; gain by factor equal to spectroscopic resolving power

focus on Oxygen (abundant; 'clean' band):

$T \sim 2.10^{6}$ K:

$$< I > \sim (1/4\pi)\, C < n_e >^{2} l\, A\, \Lambda_i\, (T_e)$$

~ 0.1 photon cm $^{-2}$ s $^{-1}$ sr $^{-1}$ **EXTREMELY FAINT!**

($l \sim (1/3)(c/H_0)$, $A \sim 0.1$ Solar)

(NB: medium probably in photoionization equilibrium with XRB, but shock-heated to 0.1 keV; collisional excitation dominates; photoexcitation important in O resonance lines!)

Spectroscopic Imaging of the Intergalactic Medium

Can get 3D distribution; abundances, sizes, densities

Diffuse emision: relevant instrument parameter is 'Grasp': product of solid angle and effective area: 'A.Ω'

For reasonable count rates (background!), need $A.\Omega \sim 0.1$ cm^2.sr; XMM/EPIC: $A \sim 500$ cm^2 at 500 eV, $\Omega \sim 10^{-4}$ sr, but: resolving power only 1/5! not enough contrast, in spite of reasonable count rates. Chandra ACIS is somewhat worse.

Experiment requires high resolution (~1 eV, large A.Ω, large FOV (several square degrees), ~sub-arcminute angular resolution soft X-ray imaging spectroscopic survey:

requires dedicated instrument.

Summary

* $z > 0$ absorption by intergalactic medium:
  possible detection of O VII resonance line, $z = 0.01$, in Mkn 421

* Absorption $z = 0$ seen in all directions (multiple objects, all instruments): most probably the Local Group ICM

* Emission from filaments $\delta \sim 50$-100 seen in broad-band images;
  in two cases: probably densest phase of the (true) WHIM.

* Absorption studies Chandra, XMM: will demonstrate the principle, but will not see 'Forest' (not enough bright targets)

* Emission with Chandra/XMM: will probably find a few examples, but sensitivity to $\delta \sim 10$'s too low. No redshift, *T*, *n*, *l*, *A*.

* Case for dedicated high resolution, large $A.\Omega$ spectroscopic imaging experiment